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C. Schippel / F. Schwierz/ J. Fu

On the f_{max} vs. f_t Characteristics for Different Types of Si-based RF Bipolar Transistors

Abstract

The cutoff frequency f_t, the maximum frequency of oscillation f_{max} and the collector-emitter breakdown voltage BV_{CEO} are computed for various types of Si-based bipolar transistors with different SIC profiles. In particular the influence of the SIC profiles on the f_t vs. BV_{CEO} and f_{max} vs. BV_{CEO} characteristics is investigated. Subsequently, the f_{max} vs. f_t behaviour is discussed. It is shown that for slow transistors (BJTs) there is a trade-off between f_t and f_{max}. However, in the case of the faster HBTs this trend can be reversed.

1 Introduction and Motivation

For RF bipolar transistors with optimised emitter-base designs, the overall performance becomes increasingly sensitive to the influence of external parts of the device like the polyemitter and the extrinsic base. Furthermore, the collector region is of particular importance since it partially belongs to the inner transistor due to the collector-base space charge region and accounts for a significant fraction of the parasitic collector resistance R_C. Therefore it directly affects the figures of merit (FoM) cutoff frequency f_t, maximum frequency of oscillation f_{max}, and the collector-emitter breakdown voltage BV_{CEO}. In modern RF BJTs and HBTs the collector is usually designed as selectively implanted collector (SIC). Therefore in the present work we investigate the influence of various SIC profiles on f_t and f_{max} with respect to BV_{CEO} for four basic types of Si-based bipolar transistors: A SiGe HBT with a graded Ge content in the base(*HBT1*), and second SiGe HBT having a much higher Ge content in the entire base (*HBT2*), thus allowing a higher dopant concentration in the base than in the emitter. In addition, two conventional NPN BJTs with diffusion (*BJT1*) respectively drift (*BJT2*) as the dominant mechanism for the electron transport through the base were investigated.

1.1 Definition of f_t, f_{max}, and BV_{CEO}

While applying a constant collector-emitter voltage V_{CE} of 2.5V to the device, the base-emitter voltage V_{BE} was increased from 0.5V to 1V. At each operating point a small-signal analysis has been performed at a fixed frequency f of 8GHz (*BJTs*) or 15GHz

(*HBTs*) and the hybrid (h) and conductance (y) parameters have been extracted. Afterwards, the cutoff frequency f_t was calculated according to

$$f_t = f \cdot |h_{21}|. \tag{1}$$

Similary the maximum frequency of oscillation f_{max} has been obtained according to

$$f_{max} = f \cdot \sqrt{U} \tag{2}$$

with the unilateral power gain

$$U = \frac{|y_{21} - y_{12}|^2}{4[\Re(y_{11})\Re(y_{22}) - \Re(y_{12})\Re(y_{21})]}. \tag{3}$$

1.2 Accuracy of the Simulated Results

The DC and RF characteristics of bipolar transistors have been simulated using the 2-D device simulator *ATLAS* [1]. Most importantly, the hydrodynamic transport model and the Katayama-Toyabe impact ionisation model [2] have been applied. To determine whether the selected set of models and model parameters is appropriate, the characteristics of an experimental HBT and its simulated counterpart have been compared. As shown in Fig. 1, we achieved very good agreements

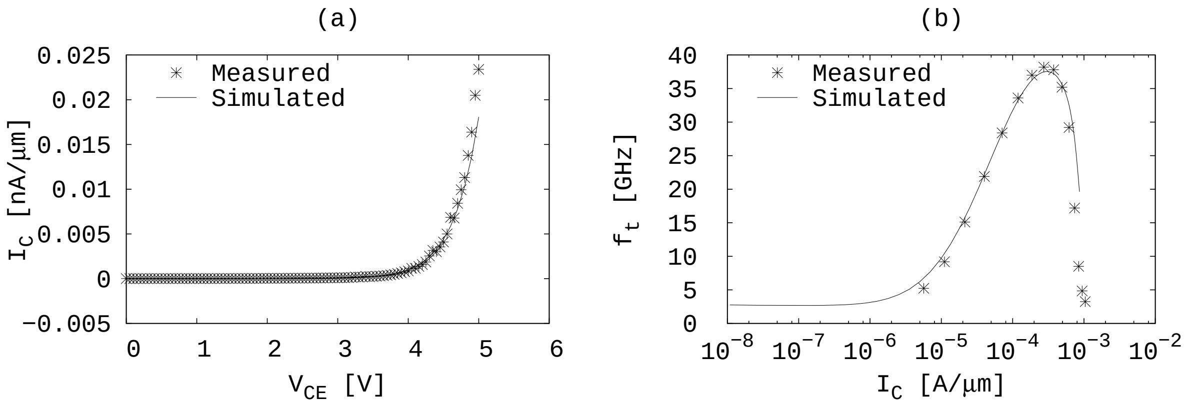

Figure 1: Comparsion of measured and simulated results:(a) open base characteristics and (b) $f_t(I_C)$ characteristics (emitter area $A_E = 0.5x1\mu m^2$)

for both the breakdown characteristics (a) as well as the dynamic behaviour (b).

1.3 Device Structures and Profiles

We considered symmetric device structures with an emitter length of $0.5\mu m$ and a lateral separation between the emitter and base contacts of $0.75\mu m$. The *BJTs* and the *HBT1* have similar vertical dimensions with base widths of about $75nm$ and base-subcollector seperations of $1.5\mu m$. *HBT2* is a device with vertically scaled emitter and

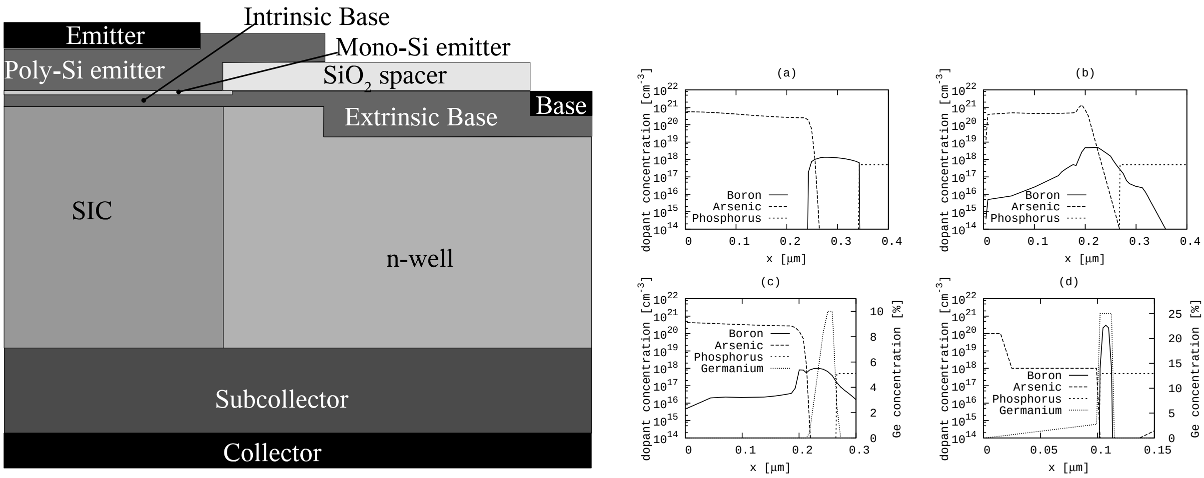

Figure 2: Structure of the simulated devices and emitter/base profiles of the transistors: (a) *BJT1*: Due to the constant boron concentration in the base the diffusion of the electrons is the dominant transport mechanism. (b) *BJT2*: A graded boron profile results in an additional drift component to the electron transport. (c) *HBT1*: The graded Ge content leads to an accelerated electron transport. (d) *HBT2*: A high boron concentration allows a thin base and thus a short base transport time.

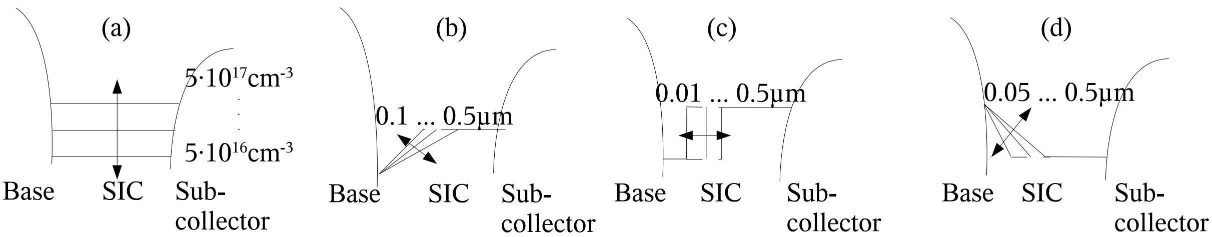

Figure 3: Basic types of SIC variations: (a) Constant, (b) graded, (c) steplike and, (d) retrograde profiles.

base regions (base width ca. $20nm$). For each of the four types of transistors, the emitter and base profiles were kept unchanged, while the profile of the SIC (i.e., the collector region underneath the emitter window) was varied according to the following rules. For each transistor type four classes of variation were made:

(a) Constant SIC profiles between base and subcollector with doping levels between $N_D = 5 \times 10^{16}$ and 5×10^{17} (*HBTs*) respectively $8 \times 10^{17} cm^{-3}$ (*BJTs*), see Fig. 3(a). Commonly with rising doping concentrations f_t and f_{max} increase, while BV_{CEO} declines.

(b) Graded SIC profiles with a dopant concentration of $N_D = 5 \times 10^{16} cm^{-3}$ at the base-collector junction and an exponential increase towards the collector up to $8 \times 10^{17} cm^{-3}$ for the *BJTs* and $5 \times 10^{17} cm^{-3}$ for the *HBTs*. The length of the graded region has been varied between 100 and $500nm$, see Fig. 3(b). When increasing the length of this slope, BV_{CEO} increases while the characteristic frequencies decrease.

(c) Step-like SIC profiles, see Fig. 3(c) with a doping level of $N_D = 5 \times 10^{16} cm^{-3}$ at the base side and $N_D = 5 \times 10^{17} cm^{-3}$ (*HBTs*) or $N_D = 8 \times 10^{17} cm^{-3}$ (*BJTs*) at the collector side. The lengths of the low-doped region varies between $10nm$ and $0.5\mu m$. Obviously, wide low-doped regions lead to higher BV_{CEO} and lower f_t and f_{max} and vice versa.

(d) Retrograde profiles with a slope starting at $N_D = 5 \times 10^{17} cm^{-3}$ (*HBTs*) or $8 \times 10^{17} cm^{-3}$ (*BJTs*) and decreasing exponentially down to $N_D = 5 \times 10^{16} cm^{-3}$ over distances between $50nm$ and $0.5\mu m$, see Fig. 3(d).

2 Results

From the simulated results the values of f_t, f_{max} and BV_{CEO} have been extracted and the f_t vs. BV_{CEO} (see Fig. 4) and f_{max} vs. BV_{CEO} (Fig. 5) characteristics have been compiled. In general, for a given BV_{CEO} the highest f_t can be achieved with steplike

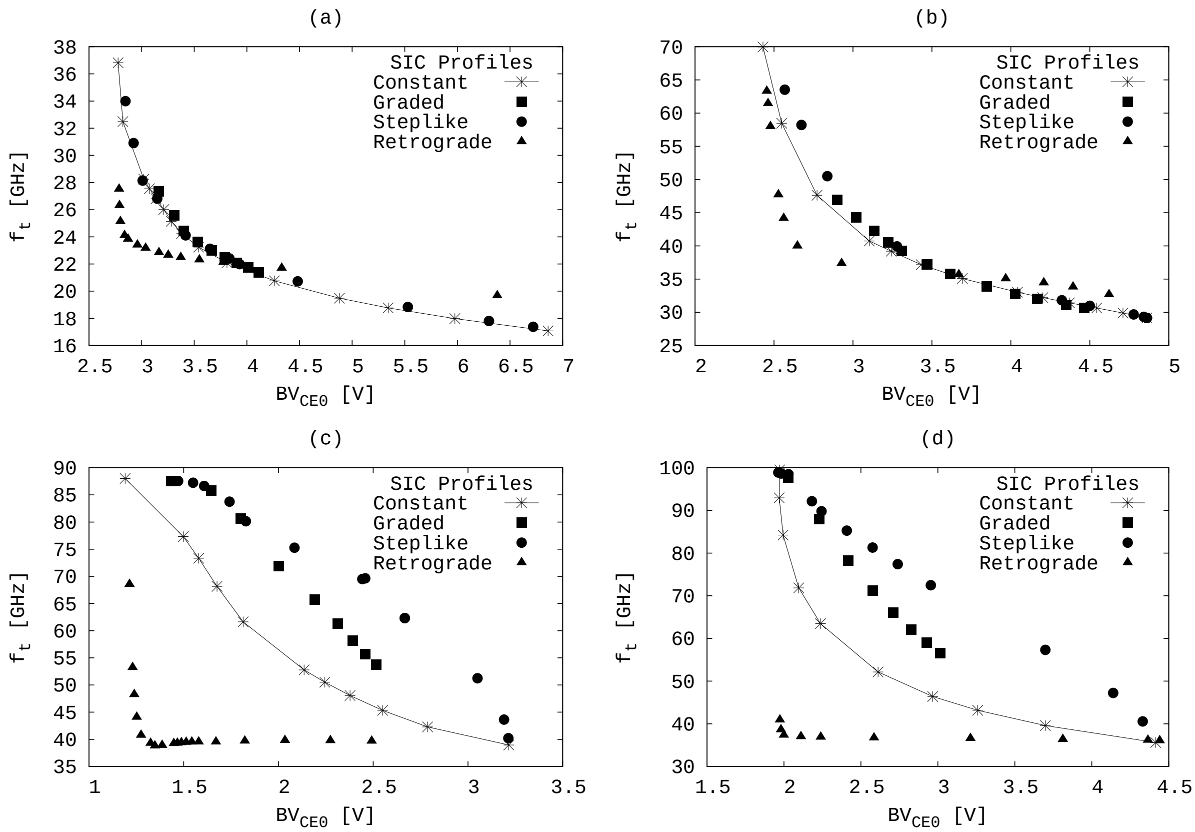

Figure 4: $f_t(BV_{CEO})$ characteristics of the four investigated classes of bipolar transistors: (a) *BJT1*, (b) *BJT2*, (c) *HBT1*, (d) *HBT2*.

profiles, followed by graded and constant ones. Retrograde dopant distributions perform at worst. However, the degrees of these trends depend on the actual transistor type. So, for diffusion BJTs these differencies are negligible, and 10% at most for drift BJTs. Contrary, for the HBTs improvements of more than 10% are common. The effects of the various SIC profiles on f_{max} are more diversified. For the slow BJTs the

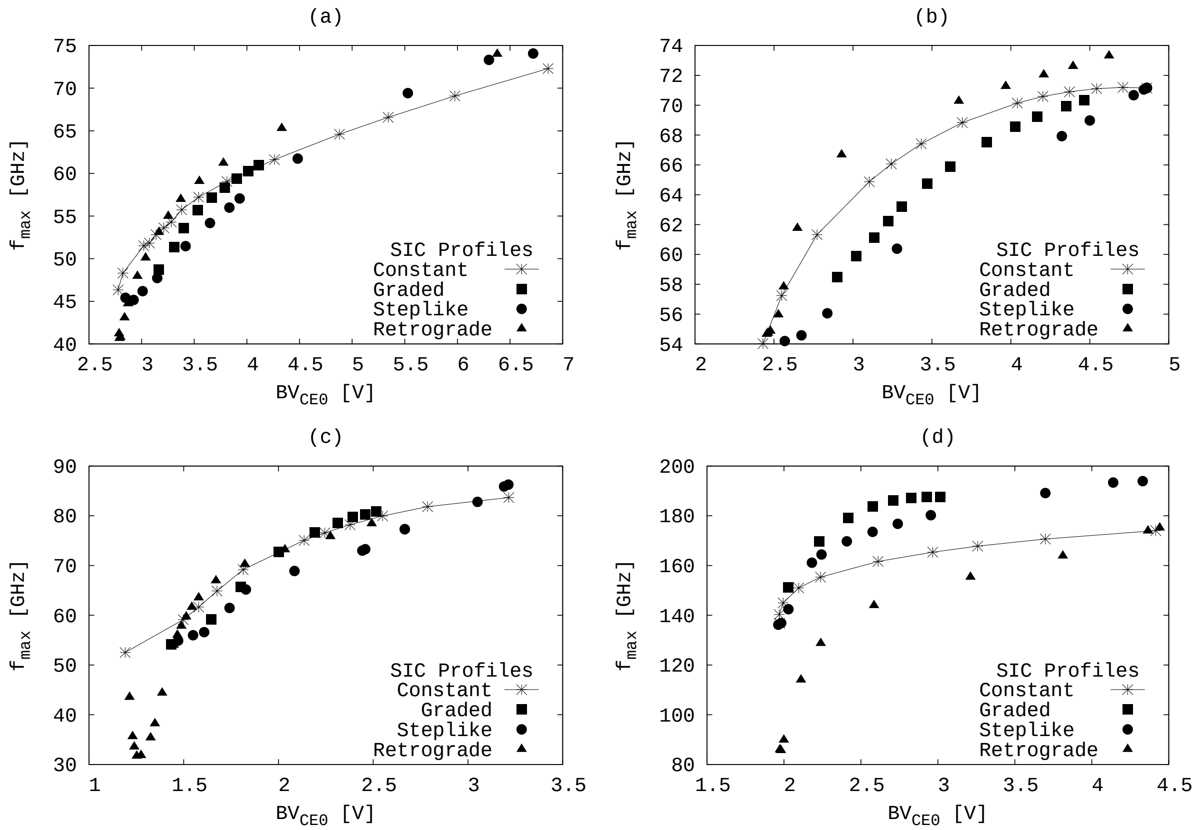

Figure 5: $f_{max}(BV_{CEO})$ characteristics of the four investigated classes of bipolar transistors: (a)*BJT1*, (b) *BJT2*, (c) *HBT1*, (d) *HBT2*.

differences in f_{max} are more pronounced than in f_t. Additionally there is a trade-off between f_t and f_{max} for these devices, i.e., transistors with higher f_t values show a lower f_{max} and vice versa. In contrast, within wide ranges of BV_{CEO} the HBTs with a

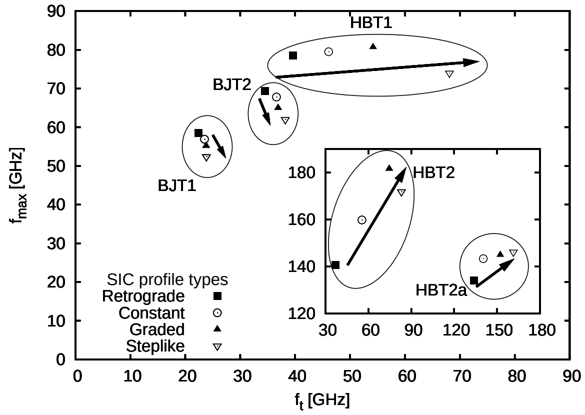

Figure 6: f_{max} vs. f_t characteristics. A note to the data of *HBT2a*: It features the same emitter/base design as *HBT2*. However, the base-subcollector seperation is reduced to $100nm$ and the values for f_{max} and f_t are extracted at $BV_{CEO} = 2V$.

higher f_t show a higher f_{max} as well. In Fig. 6 these trends are displayed in the f_{max} vs. f_t characteristics for the four types of transistors for fixed collector-emitter breakdown voltages (3.5V for BJTs, 2.5V for HBTs), which have been obtained by linear interpolation from the f_{max} vs. BV_{CEO} resp. f_t vs. BV_{CEO} characteristics. It shows that the magnitude as well as the direction of SIC profiles' influence on the FoM depend on the actual type of RF transistor.

Regarding Fig. 6 note the following: While the general design of the *BJTs* and the *HBT1* is derived from either commercially or experimentally manufactured transistors, the structure of *HBT2* is highly unusual and disadvantageous. Bipolar transistors with such thin bases feature short base-subcollector separations as well. Therefore an additional HBT-design (*HBT2a*) has been introduced, whose vertical structure is similar to common experimental devices.

3 Discussion

The results achieved cover several aspects of the collector design of bipolar transistors. First, in the case of slow devices, the collector profile has only a small effect on the f_t vs. BV_{CEO} characteristics. In these transistors the electron transport through the base dominates the performance of the devices. Therefore the influence of the optimisation of adjacent device regions, such as the collector, is limited. In other words, the product of collector-emitter breakdown voltage and cutoff frequency, $f_t \times BV_{CEO}$, is roughly constant. This is a well known property of BJTs and closely related to the Johnson limit [4]. On the other side, the f_t vs. BV_{CEO} characteristics of the investigated HBTs depend significantly on the selected doping distribution in the collector. Here, the base transit time τ_B is much shorter and therefore less important to the emitter-collector transit time τ_{EC} which determines f_t. So, the transit times of the collector τ_C and the base-collector space charge region τ_{BC} gain influence. Since both are determined by the collector, its doping profile becomes important. Thus, with a properly designed (step-like or graded) SIC profile noticeable gains in f_t can be achieved without sacrifices in BV_{CEO}. A more detailed treatment of these HBT properties is given in [3]. Regarding the maximum frequency of oscillation, the correlation between f_{max} and f_t is given by

$$f_{max} = \sqrt{\frac{f_t}{8\pi R_B C_{CB}}} \tag{4}$$

where R_B is the base resistance and C_{CB} is the collector-base capacitance. This shows the dependency of f_{max} on f_t and C_{CB}. Since the results indicate that devices with high f_ts tend to have a high C_{CB} as well, C_{CB} dominates and f_{max} decreases despite the small rise of f_t. For faster HBTs the significant increase in f_t outweighs the effects of C_{CB}, and f_{max} increases with f_t.

4 Conclusion

Regarding the design of SIC profiles there is a trade-off between the f_t and f_{max} for (slow) BJTs. It has been shown, however, that at least for certain ranges of BV_{CEO} the SIC of fast HBTs can be designed in a way that both f_t

and f_{max} benefit from an optimised design without a deterioration of BV_{CEO}.

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